Dynamics of CMEs in Interplanetary Space

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INTRODUCTION

LASCO observations

- ➤ Most CMEs can be interpreted as flux ropes (*Chen et al.* 1997)
- ➤ CME dynamics observed up to 30 Rs ⟶ Modeling limited to 2 – 30 Rs

- SECCHI observations – much wider field of view than LASCO
  - ➤ New challenges and opportunity to test the flux-rope hypothesis and our understanding of CME dynamics

- Magnetic clouds (MCs) defined by *Burlaga et al.* (1981) are the current channels of CME flux ropes (*Kunkel and Chen* 2010)

- This talk, analyse CME propagation from the Sun to 1 AU by using Flux Rope Model
  - ➤ Examine dynamics as a diagnostic of flux ropes: Characteristic magnetic forces

- I will focus on what determines the B field at 1 AU and show that
  - ➤ the CME height-data trajectory alone allows us to predict the B field at 1 AU and
  - ➤ the strength of B field and the CME arrival time at 1 AU depend on the amount of poloidal magnetic energy injected.

Initial Structure:

- Flux rope parameters: Specify Z, S_f, R/a
  - Footpoint separation distance is fixed
  - R = determined by Z, S_f
  - Set $R_0/a_0 = 2$ (based on previous work)

- Pressure: p_a (Z) = outside flux rope (model), $\bar{p}_0$ = inside (specified, usually $p_a/2$)

- B_c = overlying coronal field (specified)

- Initial Equilibrium: forces are balanced
  - Electric currents: I_t, I_p (calculated)
  - Magnetic field: B_p, B_t (calculated)
  - Total mass: M_T (calculated)
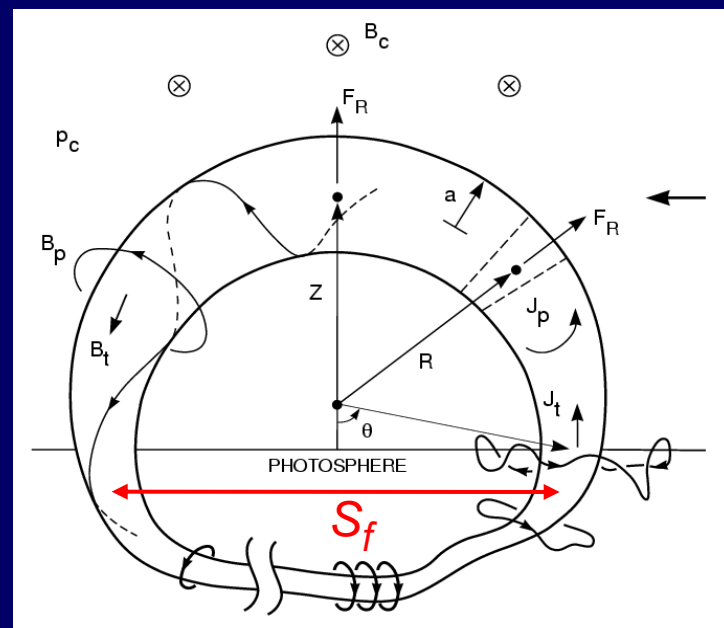
PHYSICS OF CMEs: Forces

- "Toroidal" magnetic flux rope *with fixed footpoints* separated by S_f

- Major Radial Forces: integrate $\mathbf{f} = \rho\, d\mathbf{v}/dt = c^{-1}\mathbf{J}\mathbf{x}\mathbf{B} - \nabla p + \rho\nabla\phi_g$

$$M\frac{d^2Z}{dt^2} = \frac{\Phi_p^2(t)}{c^4 L^2 R}\left[\ln\left(\frac{8R}{a}\right) + \frac{1}{2}\beta_p - \frac{1}{2}\frac{B_t^2}{B_p^2} + 2\left(\frac{R}{a}\right)\frac{B_c}{B_p} - 1 + \frac{\xi_i}{2}\right] + F_g + F_d$$
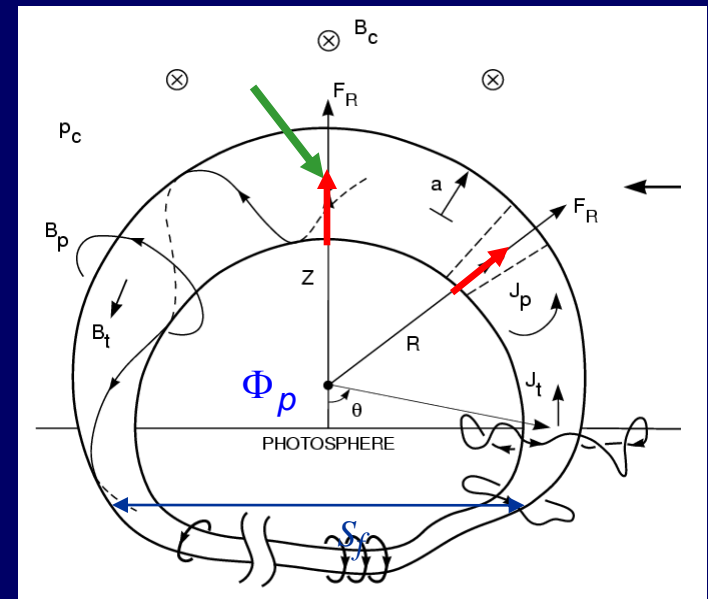
(over the bracket terms, left to right) $J_t \times B_p$, ∇p, $J_p \times B_t$, $J \times B_c$

[*Shafranov* 1966; *Chen* 1989; *Garren and Chen* 1994]

$$M\frac{d^2a}{dt^2} = \frac{a}{4}\left(B_t^2 - B_p^2 + \beta_p B_p^2\right)$$

($J_p \times B_t$, ∇p, $J_t \times B_p$)

$$\Phi_p = cLI_t, \qquad L = 4\pi\Theta R\left[\ln\left(\frac{8R}{a_f}\right) - 2\right]$$
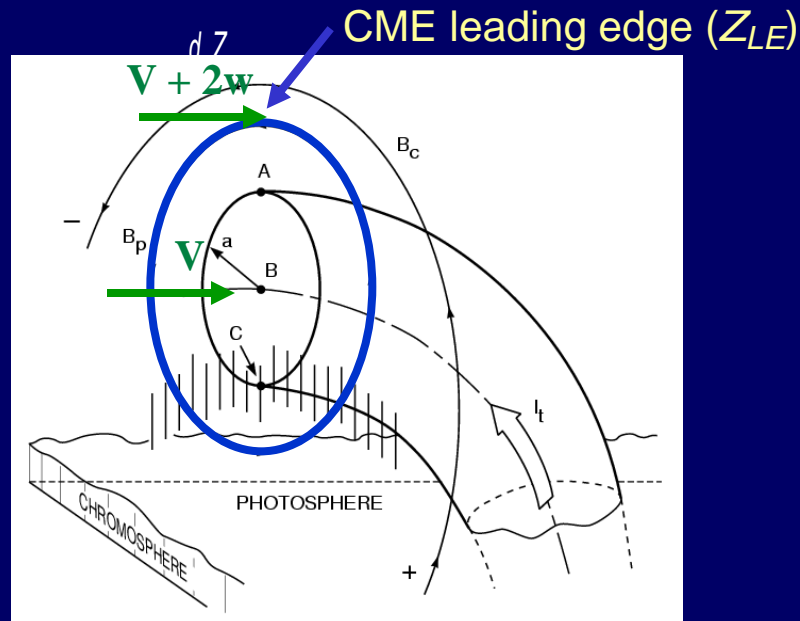
- Initiation of eruption:

$$\frac{d\Phi_p(t)}{dt} = \text{poloidal flux "injection"}$$

DRAG FORCE

- Use drag force to account for momentum coupling between the flux rope and the ambient plasma

- Drag force: the expanding flux rope displaces the surrounding plasma, transferring momentum

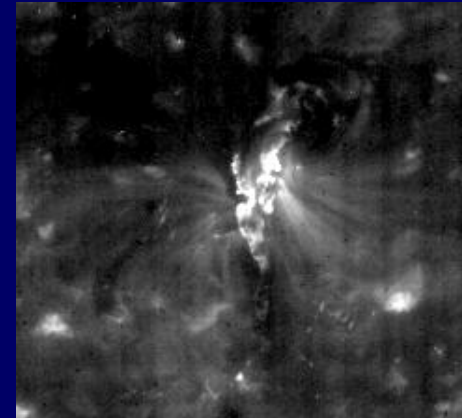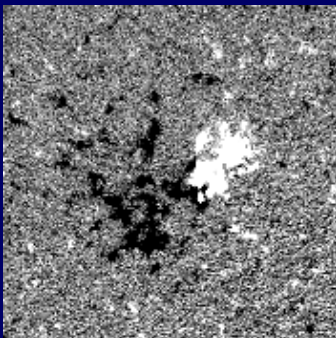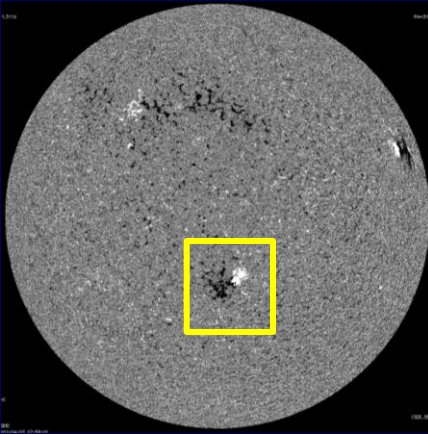$$F_d = 2C_d a \rho_{sw}[V_{sw} - (V + 2w)] \, | \, V_{sw} - (V + 2w) \, |$$

Chen (JGR, 1996)

- Initial Flux Rope (3 April 2010) source region is identified

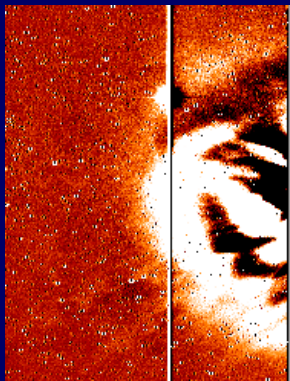   – Use EUVI and MDI data to determine footpoints (S_f), height (Z_0)

- Footpoints

    – $S_{f\,=\,1.0\ 10^{10}}$ cm
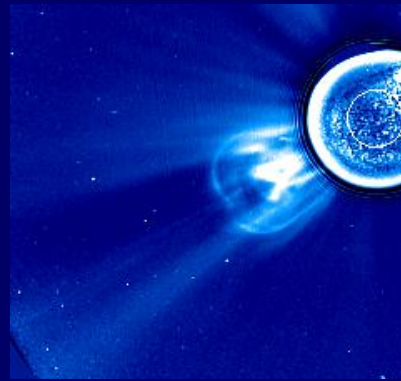
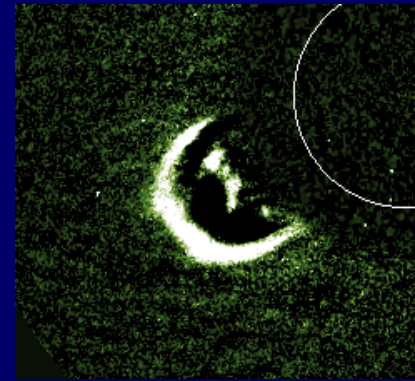   – $Z_{0\,=\,3.1\ 10^9}$ cm

    – Aspect ratio = 2

HEIGHT-TIME MEASUREMENT
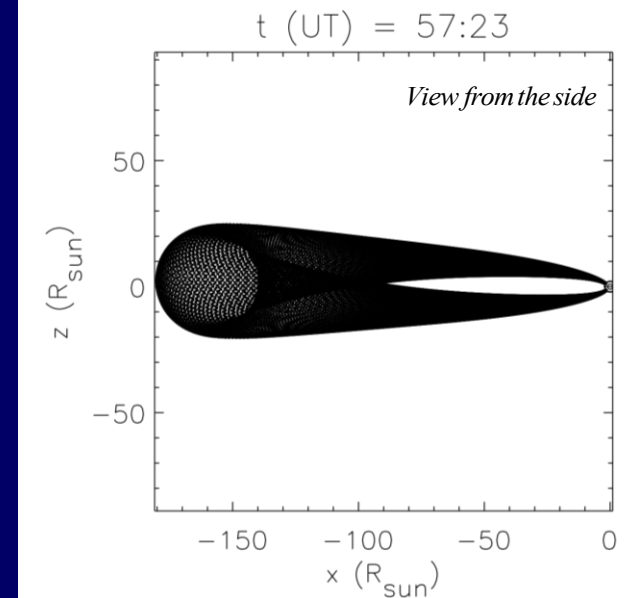
Track leading-edge height
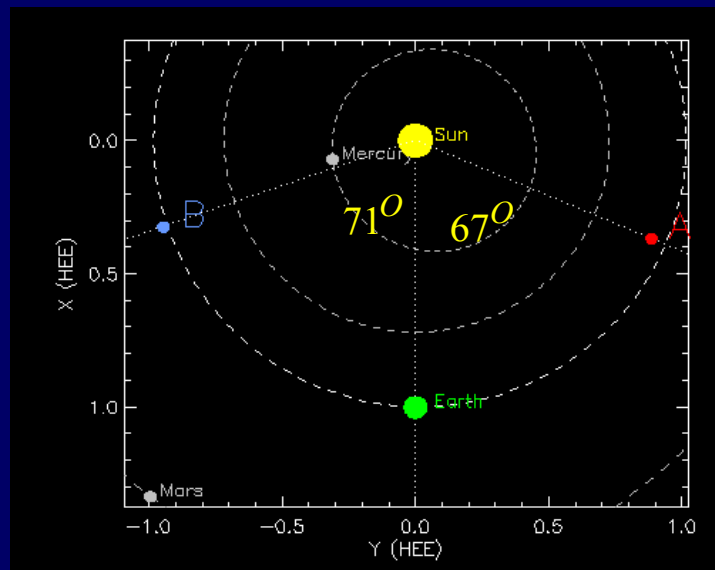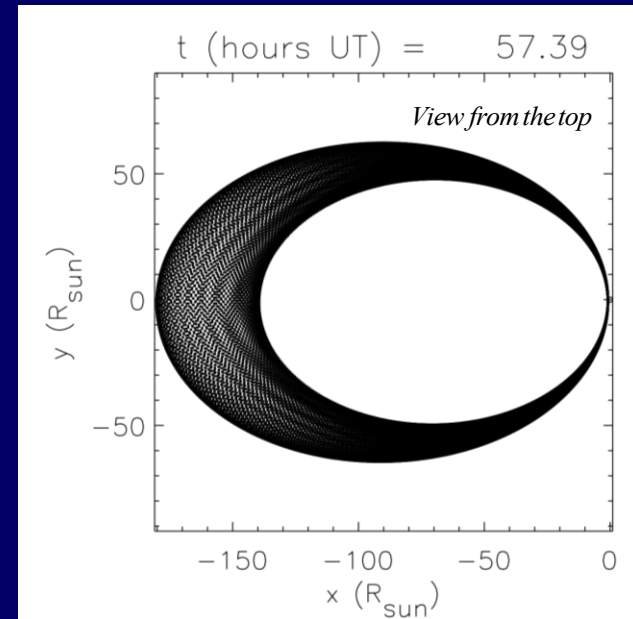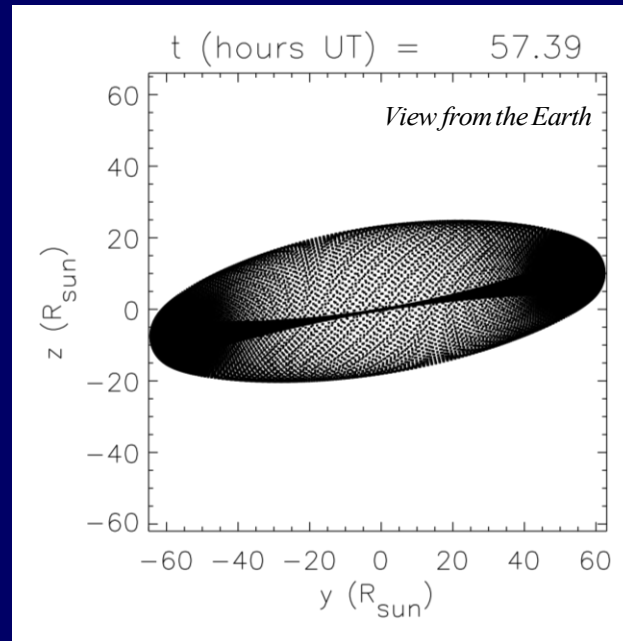

Stereo A , HI 1

Stereo A , COR 2

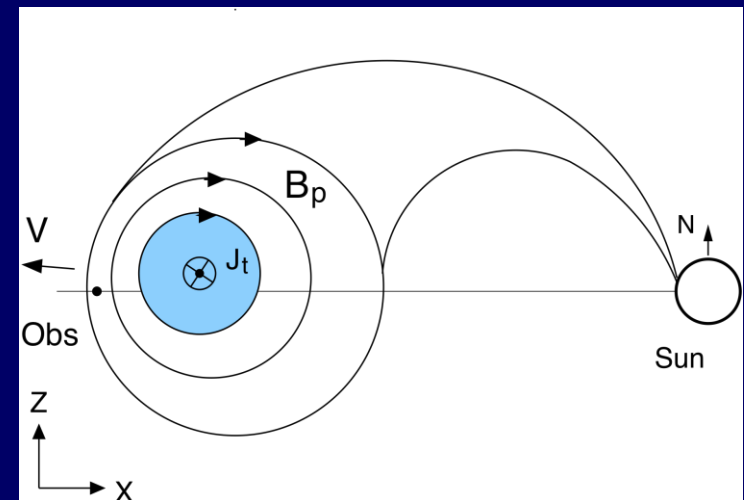Stereo A , COR 1

SYNTHETIC CORONAGRAPH IMAGES OF CME AT 1AU

$$B_p(r \mid t) = \begin{cases} 3B_{pa}\left(1 - \dfrac{r^2}{a^2(t)} + \dfrac{r^4}{3a^4(t)}\right), & r \le a(t), \\[3mm] 3B_{pa}\dfrac{r}{a(t)}, & r > a(t), \end{cases}$$
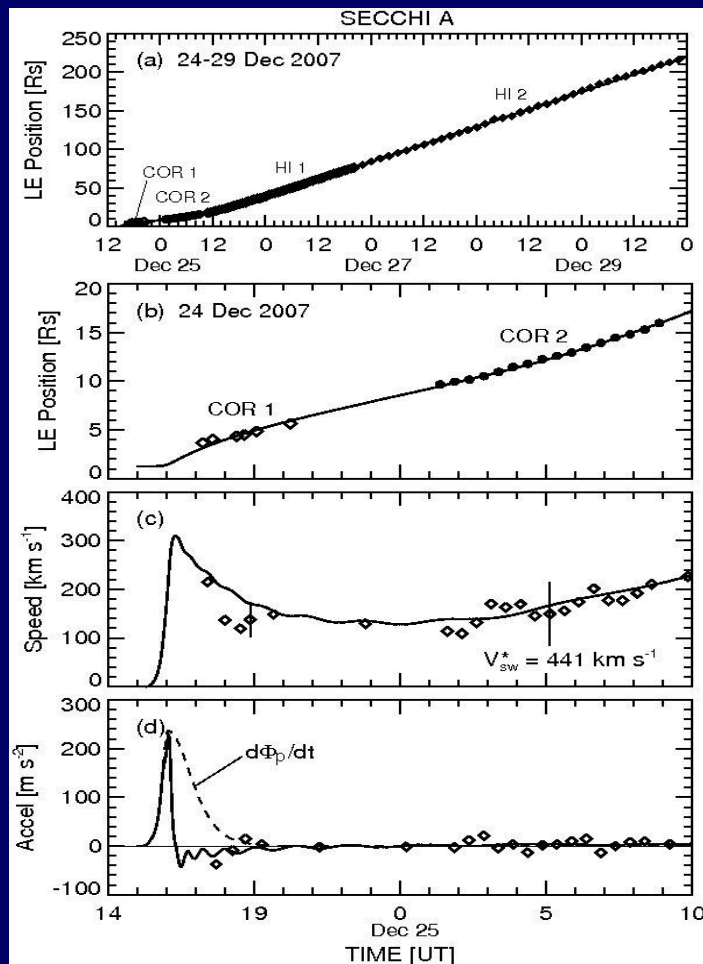

$$B_t = \begin{cases} 3B_t\left(1 - 2\dfrac{r^2}{a(t)^2} + \dfrac{r^4}{a(t)^4}\right), & r \le a(t) \\[3mm] 0, & r > a(t) \end{cases}$$

a(t) is given by the equation of motion.

SECCHI A

(a) 24-29 Dec 2007

(b) 24 Dec 2007

Interplanetary "Magnetic Cloud"

Magnetic Field at STEREO B

IMPACT Data

B_{max} =11.8 nT
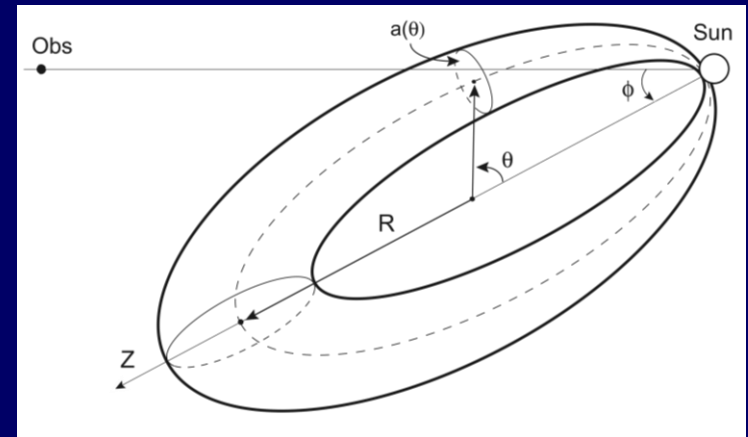
Angle of intersection with flux-rope axis — 90 deg – – – – 55 deg

Calculated *B* field and plasma data are consistent with STEREO data at 1 AU

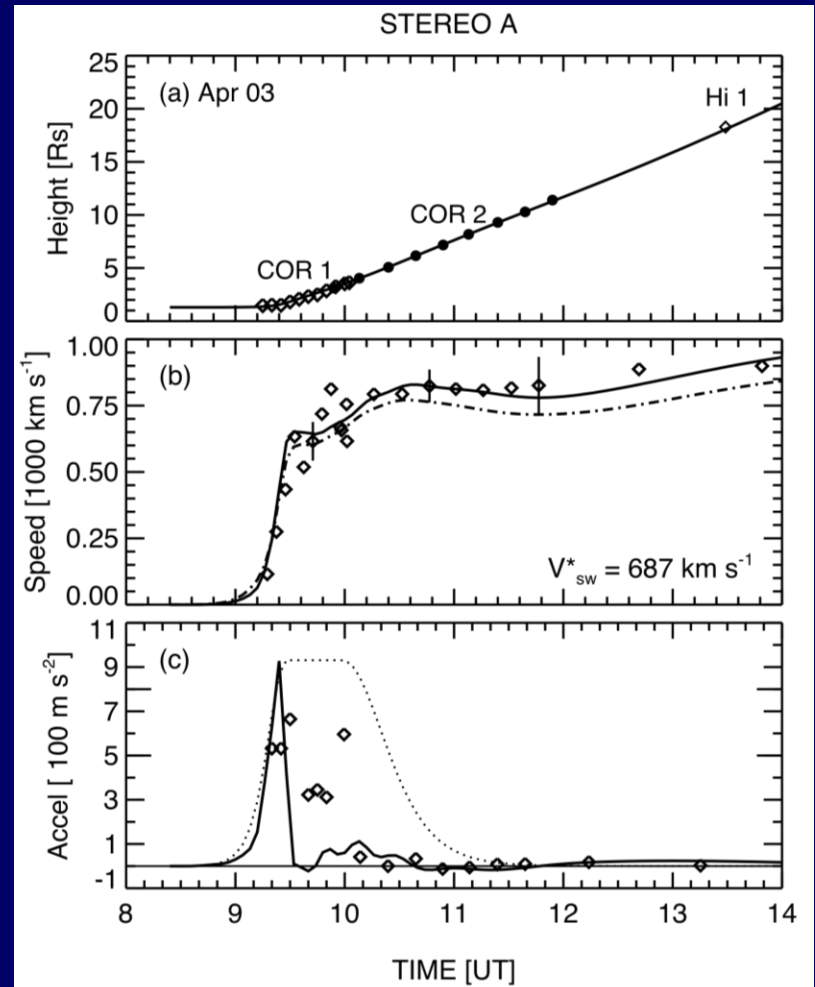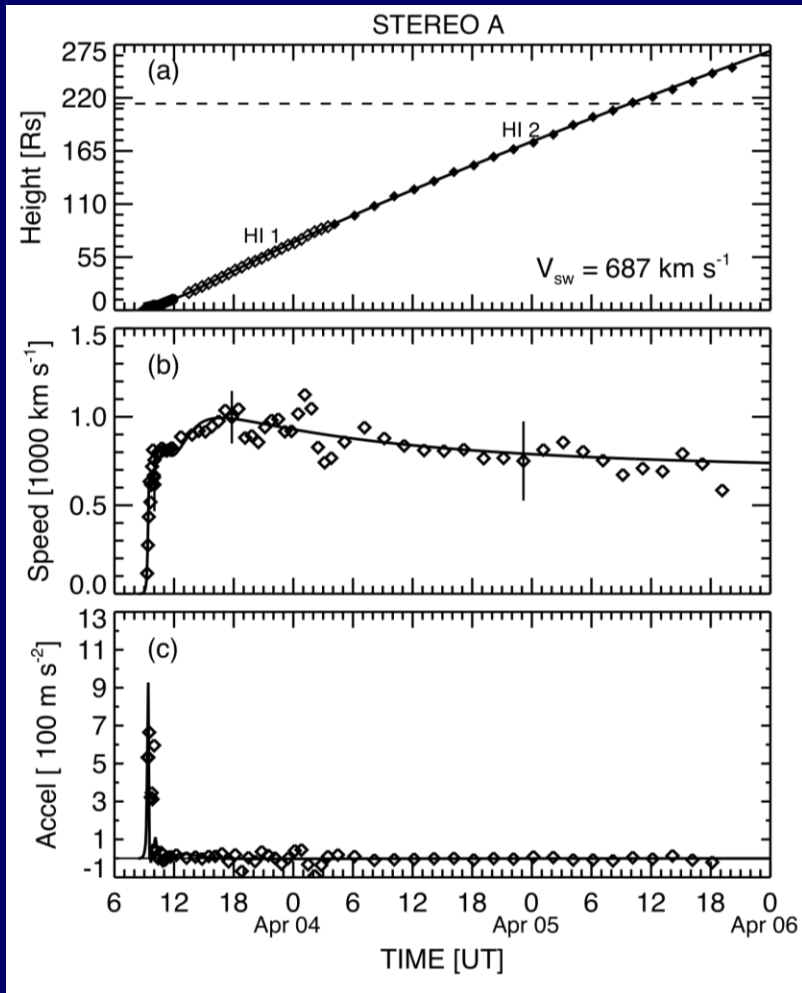Physically, MC (*Burlaga*) = current channel

MAGNETIC FIELD IN 1 AU AND S_f

Output quantities of minimum –D solutions

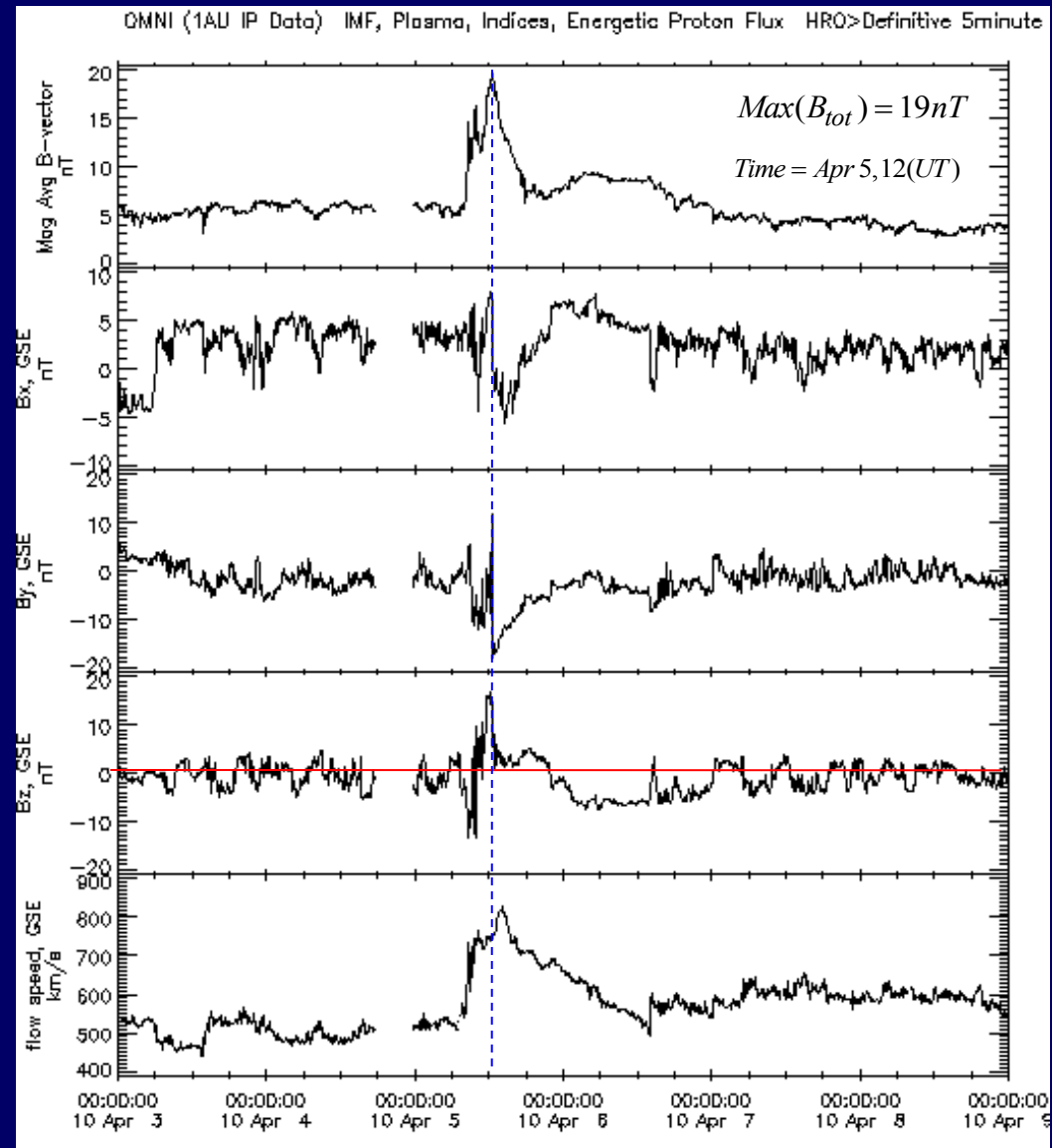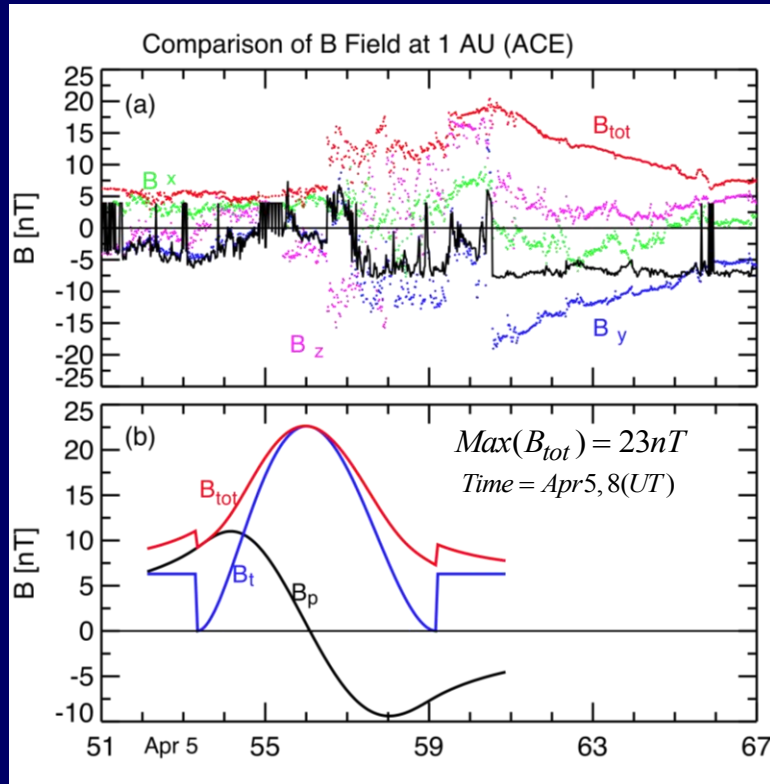Best-Fit Initial Flux Rope parameters for 2007 Dec 24 Event

G	S_f	Z_0	B_{c0}	B_{total}	V_{sw}	Arriving Time 1AU	Arriving Time 1AU
	$[10^5 \ km]$	$[10^5 \ km]$	$[G]$	$[nT]$	$[km \ s^{-1}]$	$[hours]$	$[Date / hours]$
1.75	1.0	0.4	-1.0	14.20	400	149	Dec 30, 7UT
0.96	1.2	0.6	-1.0	13.80	400	151.5	Dec 30, 9UT
0.35	1.8	0.8	-1.0	13.40	450	156.5	Dec 30, 12.5UT
0.42	2.0	0.8	-1.0	13.20	450	159	Dec 30, 15UT
0.75	2.5	1.2	-1.0	13.10	500	160	Dec 30, 18UT
1.76	3.0	1.8	-1.0	18.80	500	164.5	Dec 30, 22.5UT

THEORY FIT TO CME TRAJECTORY

Sf = 1.6e+05   Z0 = 6.0e+04   G = 0.90   tshft = 8.40

Comparison of B Field at 1 AU (ACE)

$Max(B_{tot}) = 23nT$

$Time = Apr\,5, 8(UT)$

OMNI (1AU IP Data)   IMF, Plasma, Indices, Energetic Proton Flux   HRO>Definitive 5minute

$Max(B_{tot}) = 19nT$

$Time = Apr\,5, 12(UT)$

Poloidal Flux and GOES soft X-ray flux
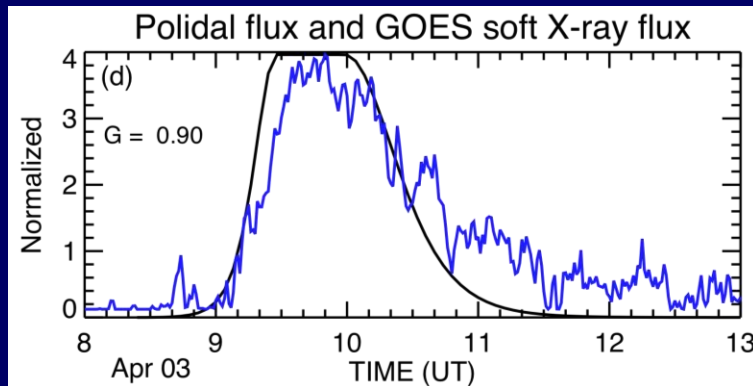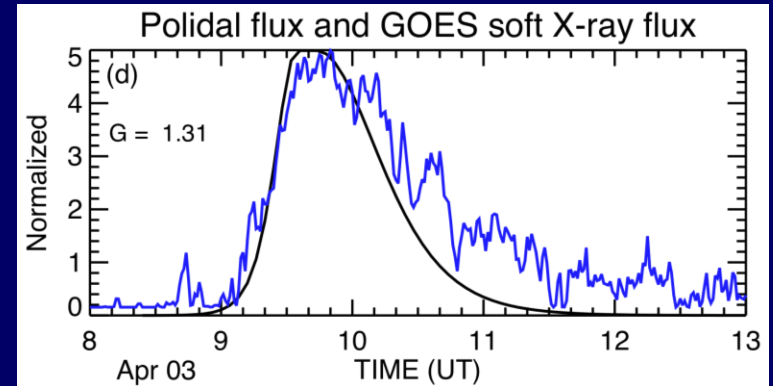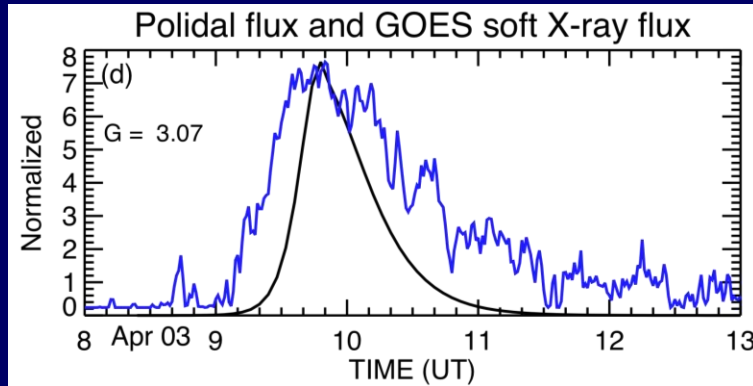
| G	Φ_{p0}	$(d\Phi_p / dt)$	$(\Delta U_p)_{tot}$	$B(1AU)$	$T(1AU)$
	$[Mx]$	$[Mx / \sec]$	$[erg]$	$[nT]$	$[UT]$
3.07	$4.55 \ 10^{20}$	$7.29 \ 10^{18}$	$8 \ 10^{31}$	23	56
1.15	$4.55 \ 10^{20}$	$4.99 \ 10^{18}$	$8 \ 10^{31}$	23	56
0.89	$4.55 \ 10^{20}$	$3.96 \ 10^{18}$	$8 \ 10^{31}$	23	56

SUMMARY

- I have studied CME propagation using STEREO data and the flux rope model

  - Comparison of model and data shown very good agreement

- The essential ingredients of the model are:

(1) The CME is a magnetic flux rope with fixed footpoints in the photosphere;

(2) The initial equilibrium structure is set into motion by injection of the poloidal;

(3) The "hoop force" (J x B) acting on the flux rope provides the acceleration;

(4) the momentum of the erupting flux rope is coupled to the ambient coronal plasma by drag

(5) the hoop force dominates in the inner corona but the drag force competes with the hoop force, resulting in both acceleration and deceleration.

- Magnetic field and arrival time of the CME at 1AU are not sensitive to the Flux injection profile provided that the injected poloidel magnetic energy is unchanged

- Compared the predicted magnetic field at 1 AU with IMPACT/PLASTIC data on STEREO finding good agreement
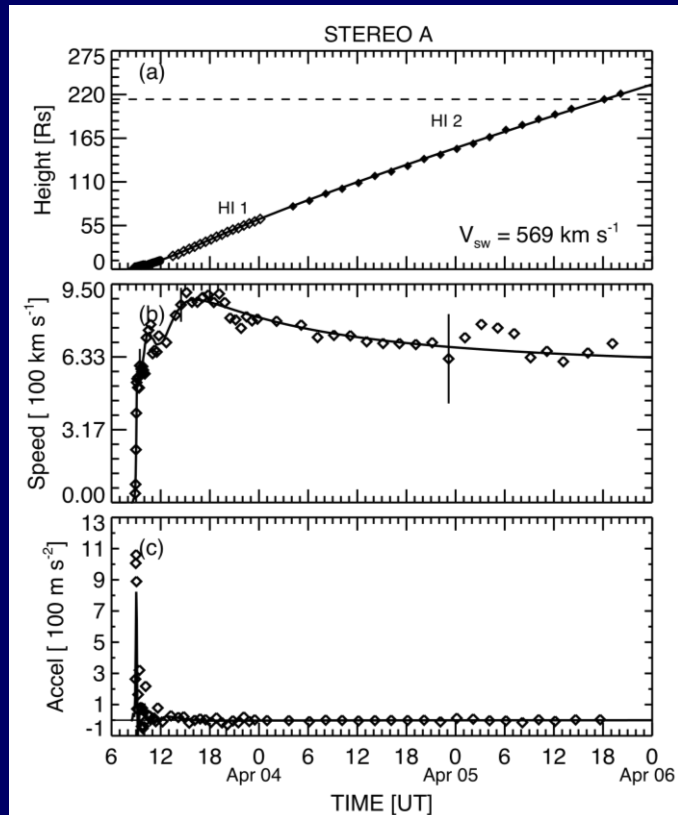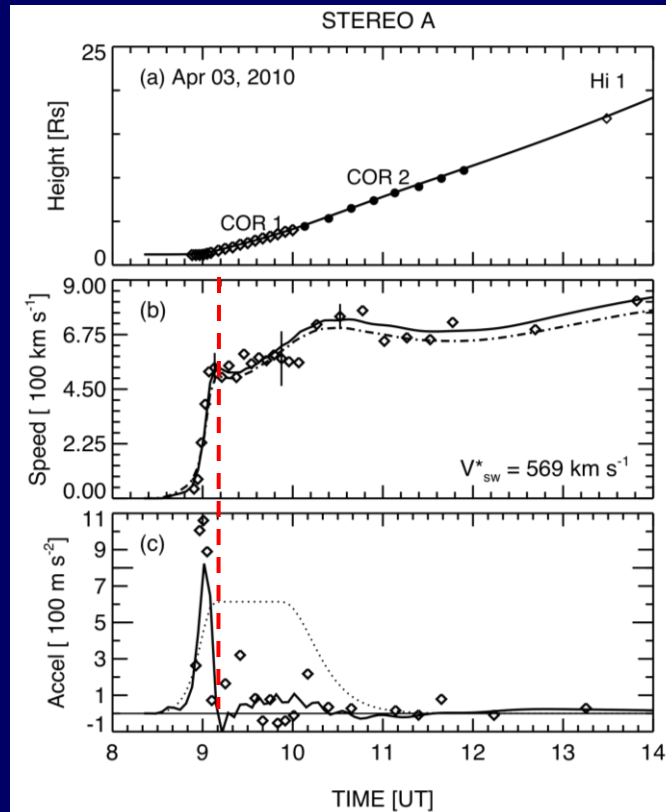
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$$B_t = \begin{cases} 3B_t\left(1 - 2\dfrac{r^2}{a(t)^2} + \dfrac{r^4}{a(t)^4}\right), & r \le a(t) \\[3mm] 0, & r > a(t) \end{cases}$$
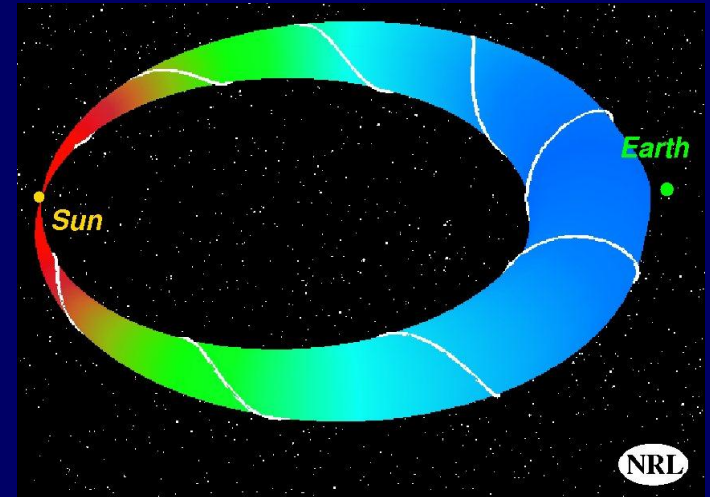
$a(t)$ is given by the equation of motion.

THEORY FIT TO CME TRAJECTORY

Sf = 1.0e+05   Z0 = 3.1e+04   G = 1.35   tshft = 8.35

Two phases of acceleration: the *main* and *residual* acceleration phases
   The main phase: Lorentz force (**J** x **B**) dominates
    The residual phase: All forces are comparable, all decreasing with height
A general property: verified in ~30 CME and EP events (also *Zhang et al.* 2001)